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Fabrication and Testing of a Blast Concussion Burst Sensor

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14. ABSTRACT
This project entails the design of passive, wearable sensors that provide an immediate and clear indication of the severity of exposure to explosive blasts, allowing soldiers with potential brain or other injuries to seek medical attention, and providing basic information about the blast to medical personnel treating such soldiers. We are developing burst membrane sensors, in which the high pressure from an incident explosive shock wave ruptures a membrane sealing a reservoir containing an indicator dye. The scope of the research involves fabricating and testing sensors in order to achieve designs that provide consistent performance at several specific pressure thresholds, as well as considering secondary issues in packaging, protecting, and mounting such devices. To date, we have developed an experimental facility for testing prototype designs, developed appropriate explosive charges to simulate explosions capable of causing traumatic brain injury, and undertaken several rounds of design iterations of prototype blast concussion burst membranes.

15. SUBJECT TERMS
explosion, blast, traumatic brain injury, sensor, burst membrane

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INTRODUCTION

In this project, we seek to design passive, wearable sensors for military personnel that will provide an indication of the severity of exposure to explosive blasts, in an easily decipherable manner immediately after the fact. This will allow soldiers that may have traumatic brain injury (or other injury) that is not immediately apparent to seek medical attention, and also provide some basic information about the blast to medical personnel treating such soldiers. We are developing burst membrane sensors, in which the incident shock wave from a nearby explosion imparts high pressure levels on precisely machined membranes sealing reservoirs containing indicators such as various colors of dye. Each membrane will rupture when exposed to pressure above a different threshold, so that the color of the dye released by the device becomes an indication of the severity of the blast. The scope of the research involves fabricating and testing such sensors in order to achieve a design that provides consistent, repeatable performance at appropriate pressure thresholds, and considering secondary issues in packaging, protecting, and mounting such devices.

BODY

The project plan is divided into 6 tasks grouped into three phases: (I) Materials Characterization, (II) Membrane Design, and (III) Sensor Testing. During the first 12 months of this project, work was carried out on all three phases, including tasks 1 through 5 of the six tasks listed in the statement of work. The majority of the effort has been in tasks 4 and 5, which together form an iterative process of fabrication, testing, and redesign of burst membrane prototypes. A detailed description of the work carried out to date on each task, and the associated research findings, follows.

Phase I: Tasks 1 and 2 (Materials Characterization)

A number of materials have been explored for use as burst membranes, including glass, various metals, and plastics. Due to ease of obtaining specimens of uniform thickness and appropriate size, ease in handling during the fabrication process, transparency (and the associated ability to analyze partial membrane rupture), and suitability for laser micromachining, glass was selected as the material of choice for rapid prototyping of the burst membranes. Glass also typically undergoes brittle failure; the lack of plastic deformation reduces the potential for memory effects in which a prior blast that does not cause rupture changes the pressure threshold at which future rupture will occur. For the majority of testing done this year, we have used glass microscope cover slips of various thicknesses, which are readily available in a size suitable for prototype fabrication and testing (in our case, 22 mm squares). Potential problems with the choice of glass include the possible presence of micro-cracks or pre-stresses in the material, due to the manufacturing process. It is possible that annealing the glass at temperatures above the softening point (but below melting) will alleviate such problems; we are currently exploring the effects of annealing to determine if there is a significant change in membrane behavior.

Because the dynamic behavior of glass subject to high-speed loading (as from an explosive shock wave) is expected to be quite different from the static or quasi-static mechanical behavior, we have not conducted static tests to characterize material properties, but have moved directly to

dynamic testing of glass-membrane prototypes, as described below. The published material properties of optical glass were used to make first-cut estimates of the dimensions necessary for the membranes to achieve rupture at desired pressure thresholds (see task 3, below) and further refinements to the design have been made empirically.

Phases II and III: Tasks 3, 4, and 5 (Membrane Design and Sensor Testing)

The basic concept for the burst membrane prototypes developed under this award is a sequence of reservoirs of various colored liquids sealed by membranes that are engineered to rupture when subject to explosive shock waves above various pressure thresholds. The pressure threshold for injury to various body tissues is a function of the duration of the overpressure [1] (see Fig. 1). In turn, both the duration and peak overpressure level depend on the effective yield of the explosive and the distance from the explosion. For the application of providing an indicator for potential brain injury due to soldiers in the field, we expect overpressure durations between 1 and 20 msec. The shock wave from an explosion with yield equivalent to 1 lb TNT has an overpressure duration between 1 and 2 msec (depending on distance from the explosion) [2], and the overpressure duration increases according to the cube root of explosive yield, resulting in a duration of 10 to 20 msec from a 1000 lb TNT equivalent explosion. The range of overpressure for which a useful sensor will give indication of potential injury is between 100 and 1000 kPa (14.5 to 145 psi, or 1 to 10 atm gauge pressure). As Fig. 1 shows, eardrum rupture is likely above 100 kPa, regardless of duration, while the thresholds for injury to soft tissue and death are more highly dependant on overpressure duration.

During the past year, we have designed and constructed an experimental system to subject test specimens to controlled explosive blasts. A schematic of the system is shown in Fig. 2, and a photograph is provided in Fig. 3. An explosive charge is detonated at one end of a cylindrical tube, which channels the shock wave in a single direction. This reduces the amount of explosive necessary to produce a given pressure level at a distance from the explosion sufficient to avoid near-field effects, i.e., the shock front from the explosion is given a sufficient distance to develop into a uniform traveling wave. Along the sides of the tube are two pressure sensors that record pressure fluctuations caused by the shock wave as it passes. The time lag between the two measurements allows the speed of the shock wave to be calculated, in addition to its amplitude. A third pressure sensor is located at the far end of the tube, at the same location as the burst membranes being tested, to provide an accurate reading of the precise overpressure experienced by the membranes. Data is acquired from all three sensors at 300 kHz (a rate sufficient to accurately measure the characteristics of the shock wave) and is triggered at the same time as an electronic signal is sent to detonate the explosive charge.

In order to produce peak overpressures in the correct range, it was necessary to develop a customized explosive charge (early experimentation with commercial fireworks showed them incapable of generating sufficient pressure amplitude or the supersonic shock waves typical of larger explosions). The charges we are currently using consist of 1.0 grams of smokeless black powder and a model-rocket igniter inside a steel vessel consisting of a 1 inch threaded nipple and two end-caps. The igniter leads protrude from small, epoxy-filled holes in one end-cap (referred to as the bottom cap). The other end cap is milled to a precisely controlled thickness, ensuring that the vessel failure always occurs at the same end of the charge, and controlling the yield of

the explosion through the thickness of steel at the failure point. A photograph of a typical explosive charge and its constituent parts in shown in Fig. 4. Note that the charge is oriented in the test apparatus such that the top end-cap faces sideways across the tube, in order to avoid sending shrapnel along the tube towards the test specimens at the far end. The fixture that holds the explosive charge in place at the tube end includes an aluminum block to absorb the impact of any solid material propelled from the vessel during the explosion.

When the top end-cap is milled to a thickness of 0.05 inches (1.3 mm) the resulting explosive shock wave has characteristics shown in Fig. 5. The time-lag between sensors 1 and 2 indicates a speed of 650 m/s (about Mach 1.9), and the pressure decay after peak pressure has a time constant of approximately 1 msec (this is taken to be the overpressure duration). At sensor 1, the peak pressure level is 400 kPa, and the amplitude decreases to about 250 kPa by the time the shock front reaches sensor 2. Sensor 3, at the tube end, is oriented to face the explosive shock front head-on. For acoustic waves traveling at the speed of sound, this typically results in a doubling of the effective pressure level, due to the interference between the incoming and reflected wave. When a supersonic wave impinges upon a fixed surface, however, it can create reflected overpressures as much as eight times higher than the incident pressure level, depending on the wave speed [2]. In this case, the pressure is 1100 kPa, several times higher than the static pressure of the incident wave. To date, testing of prototype membranes has occurred using blasts similar to that shown in Fig. 5, with peak overpressure at the reflecting surface in the range 1000 ± 100 kPa. The speed and peak overpressure of the shock wave can be adjusted by altering the thickness of the failure end-cap, to a precision limited by that of the machining process (a tolerance of ±0.005 inches results in peak reflected overpressure uncertainty of about ±100 kPa). Once all design issues for the membranes have been resolved, future explosions can be adjusted to test membranes designed to fail at various pressure levels in the range 100 to 1000 kPa.

The test fixture is a 4 inch square block with four threaded holes and a central hole in which pressure sensor #3 is mounted. Twelve test specimens can be tested simultaneously by manufacturing 12 prototype burst membranes in a single 4 inch square sheet of acrylic (or other base material) and attaching the plate to the test fixture via screws. A photograph of the test fixture with 12 such test specimens in place is shown in Fig. 6.

Each prototype consists of a membrane fixed over a circular reservoir in the base plate, intended to hold a colored liquid that will spill from the device only if the membrane ruptures. In early prototypes, the diameter of the wells was varied between 0.125 and 0.500 inches; an intermediate value of 0.250 inches was selected for subsequent tests. A number of adhesives were investigated to determine a suitable method to seal colored liquid inside each reservoir, and Norland optical adhesive #68 (a waterproof, UV-cure epoxy) was selected. For several subsequent rounds of testing, the liquid has been temporarily omitted from the wells, in order to reduce needless mess and eliminate one potential source of variation between nominally identical devices. The liquid will be reintroduced in future tests to allow study of the effect of the presence of the liquid on the rupture dynamics of the membranes.

Figure 7 shows photographs of a typical membrane before and after testing. In this case, a #1 microscope cover slip (approximately 110 μm thick optical glass) was scribed with 15 passes of the beam of a 2 Watt 266 nm laser microfabrication system. The pattern shown consists of a

small circle at the membrane center and four radial lines. The glass was fixed over a 0.250 diameter reservoir in the acrylic base plate using the epoxy, and subjected to an explosion similar to that shown in Fig. 5. After testing, the glass over the reservoir has completely shattered, leaving a hole in the cover slip with the same diameter as the reservoir. Identical glass cover slips without this scribed pattern do not fail under similar test conditions.

The current goal of our research is to determine the optimal scribing pattern, depth of scribe, and assembly technique to produce consistent results, creating membranes that rupture only above a specific (and controllable) peak pressure level. There has been some degree of variation among the samples in preliminary iterations of the design, i.e., nominally identical designs do not always fail at consistent pressure thresholds. We are currently investigating several potential sources for this variation, including pre-stresses or pre-existing micro-cracks in the glass, variations in adhesive thickness or other variations in the way the devices are assembled, and variation in the results of the laser scribing process. Our short-term goal is to achieve a series of device designs in which a given design consistently remains intact when subjected to one level of shock overpressure but consistently ruptures when subjected to a level a few hundred kPa higher.

Once such designs are achieved, the remaining months of the project will focus on Task 6, in which we plan to investigate issues related to combining multiple devices in one package, protecting membranes from rupture by means other that incident explosive shock waves, and understanding variations in performance when the devices are mounted on a variety of hard and soft surfaces.

KEY RESEARCH ACCOMPLISHMENTS

- Designed and constructed a blast tube test apparatus, in which an explosion is triggered at one end, the resulting shock wave is measured and characterized as it travels along the tube, and prototype test specimens can be placed in the path of the shock wave at the far end of the tube.
- Designed custom explosive charges that can be machined in order to provide desired levels of shock overpressure in the range encompassing minor injury to fatality in humans.
- Tested several generations of burst membrane prototype designs, informing future iterations in search of consistently performing burst membranes.

REPORTABLE OUTCOMES

During year 1 of this grant, no journal articles were published or conference presentations given relating to this award. The investigators plan to prepare a journal article over the next several months to publish results obtained over the entire 18 month award period.

One graduate student, Mr. Patrick Fry, was supported using funds from this award during the past year. Mr. Fry obtained his Master of Science in Engineering degree in May 2009.

CONCLUSION

The first year of this project has resulted in development of an experimentally facility for testing prototype designs, development of appropriate explosive charges to simulate explosions capable of causing traumatic brain injury, and several rounds of design iterations of prototype blast concussion burst membranes. Over the remaining months of the project, we anticipate these iterations converging on a design that provides membranes that reliably rupture at desired pressure thresholds, and will explore performance issue related to packaging such devices, protecting them from unintended rupture, and mounting the sensors on hard or soft surfaces, such as helmets, body armor, or uniform fabric.

REFERENCES

[1] Bowen TE and Bellamy RF, eds., *Emergency War Surgery*, United States Government Printing Office, Washington, DC, 1988.

[2] G. F. Kinney, *Explosive Shocks in Air*, Macmillan, New York, 1962.

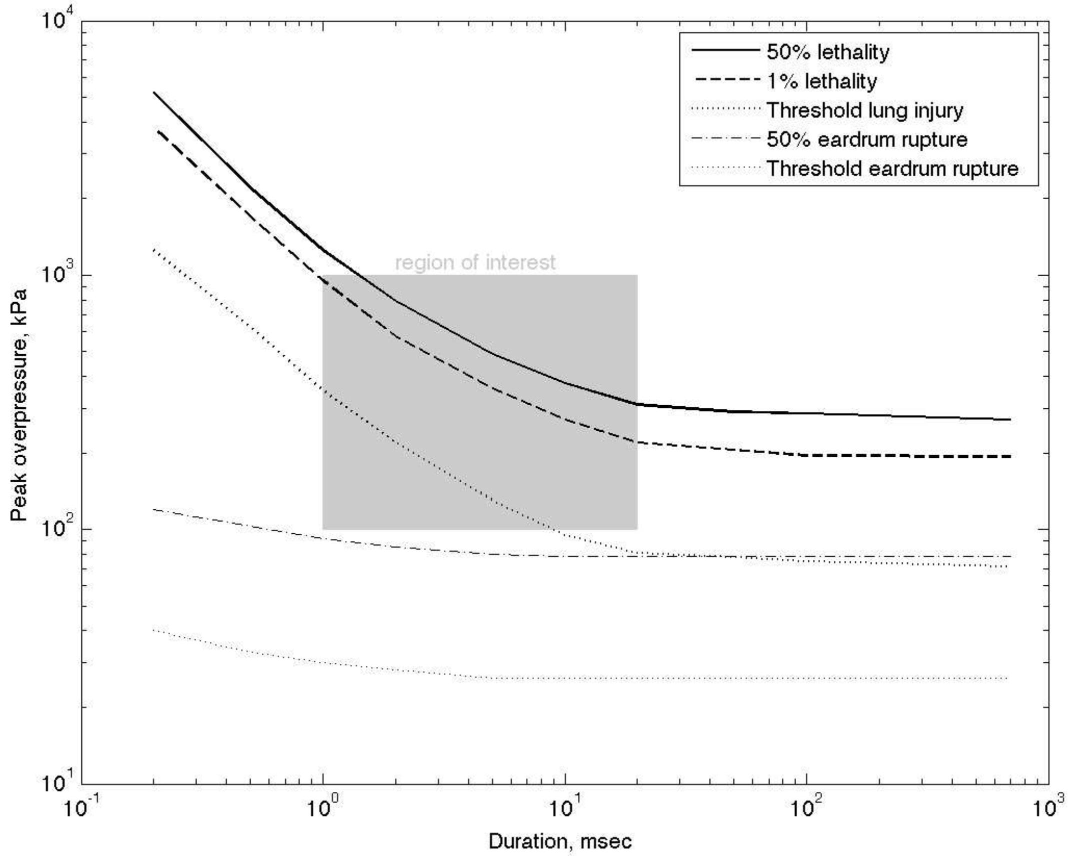


Figure 1: Thresholds of injuries as a function of blast duration and overpressure [1]. The design goal is membranes that burst at specific pressure levels between 100 and 1000 kPa when subjected to blasts with overpressure durations between 1 and 20 msec.

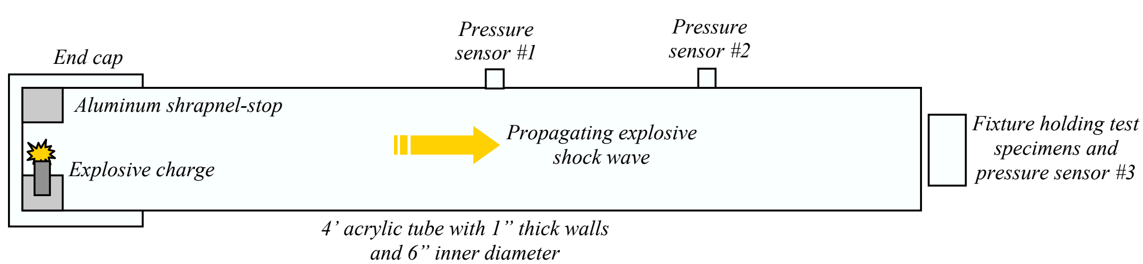
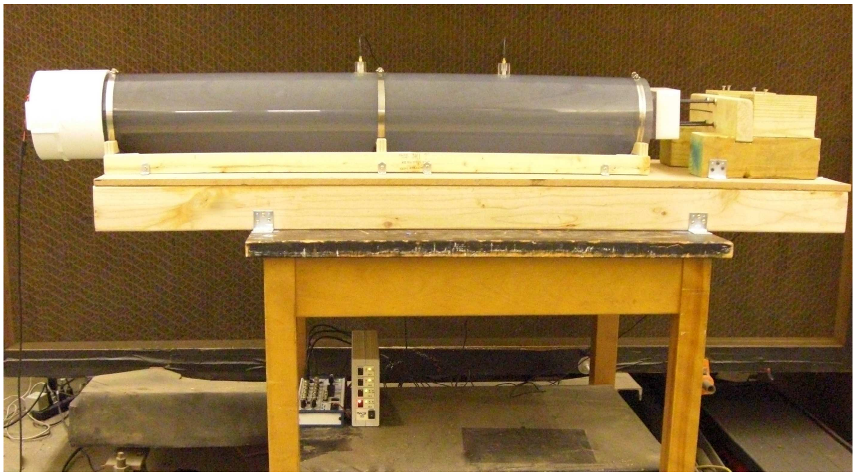


Figure 2: Schematic of blast tube test apparatus



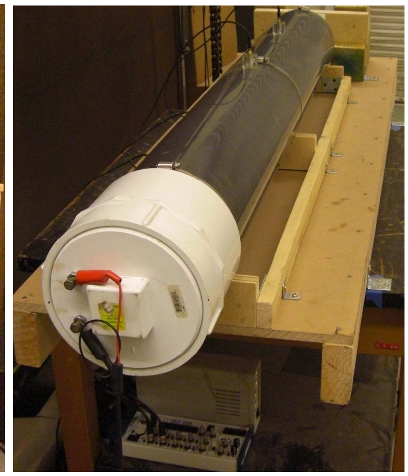


Figure 3: Photographs of blast tube for testing burst membrane prototypes. Side view (*left*) and view from end containing explosive charge (*right*).

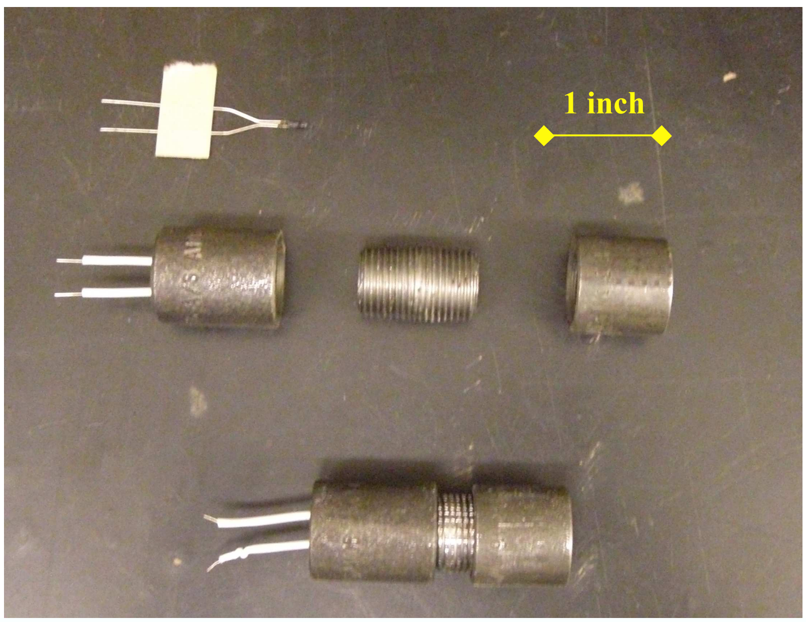


Figure 4: Components of an explosive charge, including igniter (*top left*), steel base cap with igniter epoxied inside and wires protruding (*center left*), 1 inch steel nipple (*center*), and top cap with end milled to a precise thickness to control the peak overpressure (*center right*). An assembled charge, containing 1.0 grams of smokeless black powder, is shown at *bottom*.

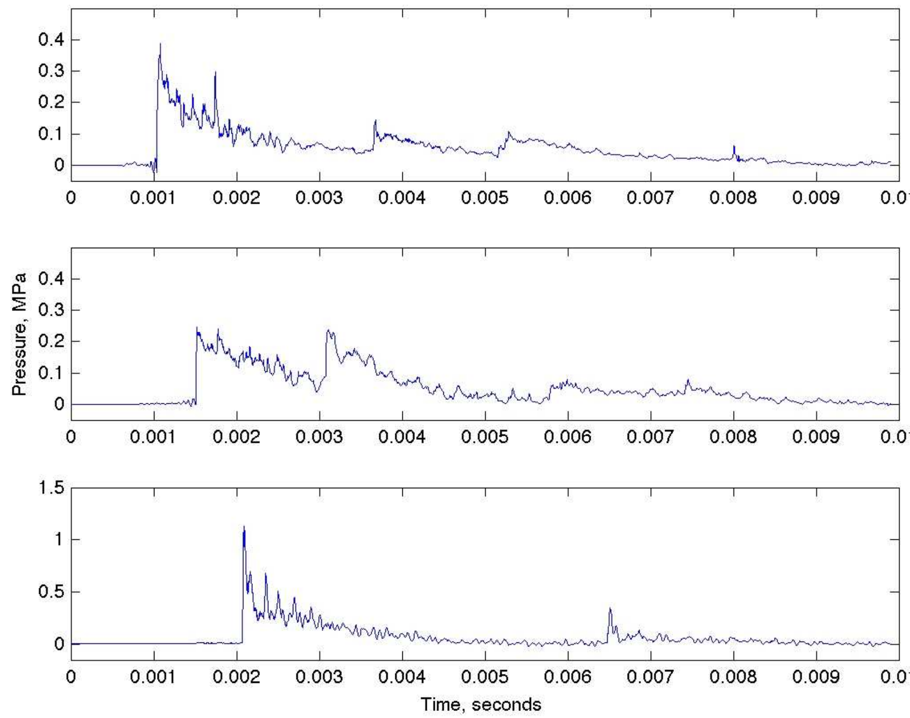


Figure 5: Pressure sensor records for a typical shock wave during prototype testing. Sensor #1 (*top*) is at mid-tube, sensor #2 (*center*) is 12 inches further along the tube, and sensor #3 (*bottom*) is at the same distance as the test specimens, at the open end of the tube furthest from the explosive charge. Note that, in addition to the initial shock front, the reflection from the test fixture is visible in the sensor #2 data (just after 3 msec) and sensor #1 data (around 3.7 msec). Secondary and tertiary reflections are also visible.

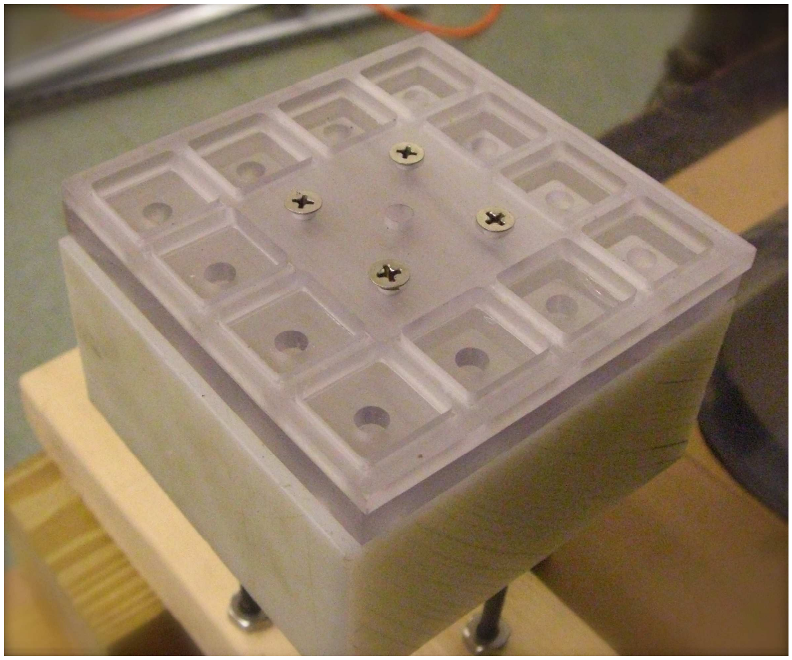


Figure 6: Photograph of test fixture holding 12 test specimens. The hole in the plate center contains pressure sensor #3.

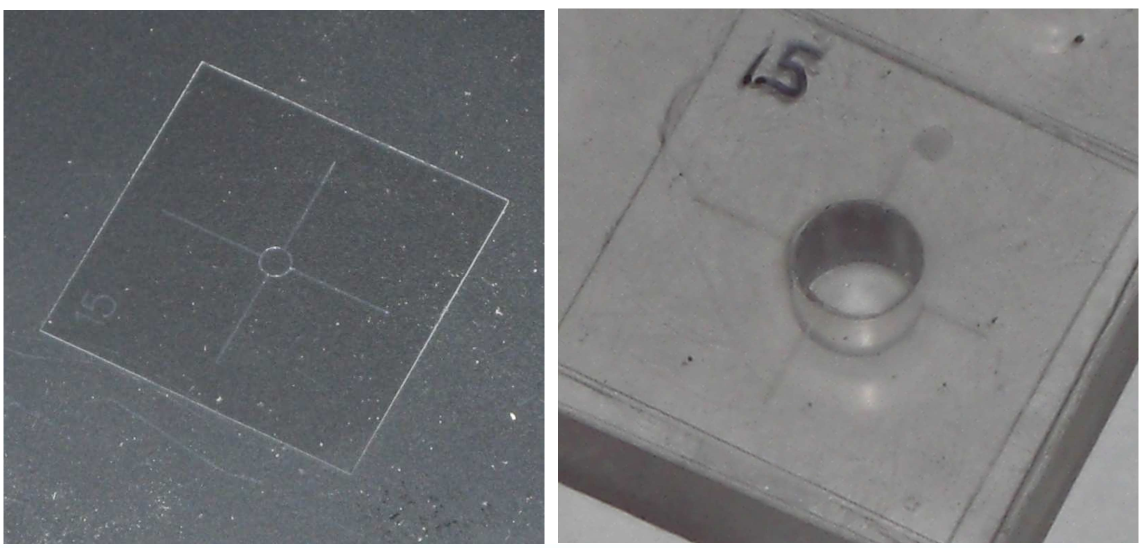


Figure 7: Photographs of scribed glass membrane (*left*) and ruptured membrane of a test specimen after testing (*right*).